Expected performance of a near-infrared nulling instrument on board the PEGASE free-flying demonstrator mission

Olivier Absil (Université de Liège), Alain Léger, Marc Ollivier (IAS Orsay),
Daniel Rouan, Vincent Coudé du Foresto, Jean Schneider (Observatoire de
Paris), Denis Mourard (Observatoire de la Côte d'Azur), Frédéric Cassaing
(ONERA), Xavier Leyre (Alcatel Cannes)

I. Context and objectives

In answer to a call for ideas for a **free-flying space mission** issued by **CNES**, a group of French and European institutes has proposed a **near-infrared nulling interferometer** to characterize Pegasides (hot Extrasolar Giant Planets) as well as brown dwarfs and proto-planetary disks. If selected by CNES, this mission would achieve **spectro-photometry of a dozen hot Jupiters** with a spectral resolution of 60 and a spatial resolution ranging between 12 mas (B=50m, λ=6μm) and 0.3 mas (B=500m, λ=1.5μm).

II. Instrumental concept

The chosen concept consists in a **Bracewell interferometer** formed of three spacecrafts: **two micro-satellites** (Myriade) bearing 40 cm siderostats for light collection and **a mini-satellite** (Proteus) for light focusing, recombination, spectroscopy, detection, free-flying configuration control and telemetry. In addition to the near-infrared nulling interferometer, a constructive interferometer will measure the visibilities in the visible range and perform **fringe tracking** with an accuracy of a few nm RMS.
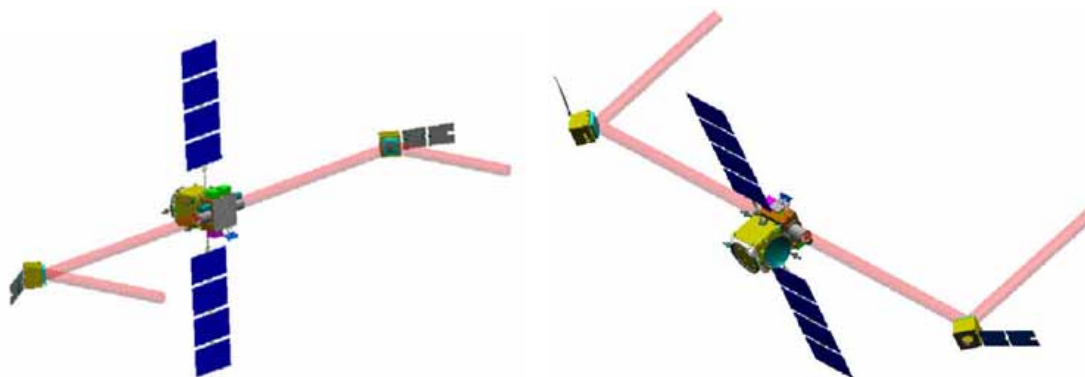

Figure 1: Conceptual views of the PEGASE free-flying interferometer.

The nulling instrument will be divided into two spectral channels (1.5 – 3 μm and 3 – 6 μm) on which **modal filtering** will be performed by means of single-mode fibres. The optical elements will be passively cooled down to 100 K and the detector (HgCdTe array) down to 55 K. The interferometer should operate at the Lagrange L2 point.

III. Simulated performance

The performance of the nulling instrument onboard PEGASE is estimated in Table 1 at λ=3 µm and R=60 for **five targets**. Four of them are hot Jupiters with various orbital parameters that have been detected by RV surveys, while the fifth one is a hypothetical "hot Uranus". In the first section are defined the **instrumental parameters**. The baseline of the configuration has been tuned so as to place the planet almost on the first bright fringe of the transmission map when at its maximum angular separation. A decisive parameter of the instrument is its ability to maintain a stable null. This ability is measured by the **instrumental nulling**: this is the nulling ratio one would get for an unresolved point-like source. Its value is determined by the contributions of **OPD** errors and **pointing** errors which induce intensity mismatches in the single-mode fibres (polarization errors are assumed negligible). Another important parameter is the instrument **temperature**, which should be kept low enough to reduce the thermal background emission.

The stellar and expected planetary parameters are listed in the following sections. The planetary temperature is computed from blackbody equilibrium. The **geometric nulling** is the rejection factor on stellar light due only to the finite extent of the stellar disk, without instrumental errors. Due to the simplicity of the configuration (only two telescopes), this factor does not reach the **initial star/planet contrast**. Thus, an additional **calibration** of the stellar leakage will be required to actually detect the planet. This calibration can be achieved through a precise measurement of the **stellar diameter** by means of the visible interferometer onboard PEGASE. Another possibility is to use the rotation of the array. In practice, both methods will be used at the same time to improve the calibration accuracy. The maximum transmission accounts for the position of the planet on the transmission map (the best SNR is not always obtained with the planet placed on the 1st bright fringe).

The last source of photons is the **thermal background emission** of the local zodiacal cloud and of the instrument itself. Its fluctuations are related to the possible temperature fluctuations of the optical elements. The local zodi emission is assumed stable in time.

The noises and signal-to-noise ratios are divided into four contributors:
- The **photometric SNR**, computed for an integration time of 1 hour, comprises the shot noise from all sources (including background) and the detector noise (mainly read-out noise: we assume a RON of 10 e⁻ rms and an individual integration time of 100 sec).
- The **instrumental SNR** is related to the fluctuations of the stellar leakage due to phase and intensity errors. The mean instrumental nulling, computed from the rms OPD and pointing error, is indeed equal to the rms fluctuation of the global nulling ratio. The required stability of the stellar leakage is about 10^{-5} of the initial stellar flux.
- The **calibration SNR** is related to the calibration of the geometric stellar leakage. Its value depends on the precision on the measurement of the stellar diameter. A precision of 0.1% has been assumed in this study.
- The **background fluctuation SNR** mainly depends on the temperature of the instrument and on its fluctuations. The mean background will be subtracted by modulation.

		Tau Boo b	51 Peg b	HD209458 b	HD162020 b	Hot Uranus
Instrument	Diameter [m]	0.40	0.40	0.40	0.40	0.40
	Total surface [m²]	0.25133	0.25133	0.25133	0.25133	0.25133
	Baseline [m]	90.00	80.00	300.00	120.00	40.00
	Wavelength [m]	3.00E-06	3.00E-06	3.00E-06	3.00E-06	3.00E-06
	Waveband [m]	5.00E-08	5.00E-08	5.00E-08	5.00E-08	5.00E-08
	Angular resolution [mas]	3.44	3.87	1.03	2.58	7.73
	Field-of-view [sr]	3.58E-11	3.58E-11	3.58E-11	3.58E-11	3.58E-11
	FoV radius [mas]	696.39	696.39	696.39	696.39	696.39
	Thruput and QE	0.03	0.03	0.03	0.03	0.03
	Emissivity x QE	0.70	0.70	0.70	0.70	0.70
	Instrument temperature [K]	100.00	100.00	100.00	100.00	100.00
	RMS temperature fluctuations [K]	1.00	1.00	1.00	1.00	1.00
	RMS OPD error [nm]	3.00	3.00	3.00	3.00	3.00
	RMS pointing error [mas]	50.00	50.00	50.00	50.00	50.00
	Instrumental nulling (mean = rms)	98667	98667	98667	98667	98667
Star	Distance [pc]	15.6	14.7	47	31.3	10
	Radius [Rsun]	1.220	1.300	1.100	0.798	1.000
	Angular radius [mas]	0.364	0.411	0.109	0.119	0.465
	Knowledge of stellar diameter	0.1%	0.1%	0.1%	0.1%	0.1%
	Teff [K]	6276	5770	6030	4890	5770
	Flux [Jy]	1.25E+01	1.42E+01	1.06E+00	9.17E-01	1.81E+01
	Geometric nulling	144.72	143.24	145.43	765.96	448.09
	Total (uncalibrated) stellar nulling	144.51	143.03	145.22	760.06	446.07
	Output flux [Jy]	2.60E-03	2.98E-03	2.19E-04	3.62E-05	1.22E-03
	Output flux [ph-el/s]	164.55	188.18	13.85	2.29	77.15
Planet	Orbit [AU]	0.050	0.051	0.045	0.072	0.050
	Max. ang. separation [mas]	3.205	3.483	0.957	2.300	5.000
	Radius [Rjup]	1.30	1.30	1.30	1.30	0.40
	Albedo	0.35	0.35	0.35	0.35	0.35
	Temperature [K]	1343	1259	1291	705	1117
	Thermal flux [Jy]	4.98E-03	4.40E-03	4.74E-04	4.76E-05	5.51E-04
	Reflected flux [Jy]	3.39E-04	3.66E-04	3.54E-05	1.20E-05	4.64E-05
	Initial star/planet contrast	2356.88	2977.68	2080.74	15401.63	30386.80
	Maximum transmission	0.989	0.976	0.987	0.972	0.722
	Output flux [Jy]	1.58E-04	1.40E-04	1.51E-05	1.74E-06	1.29E-05
	Output flux [ph-el/s]	9.98	8.82	0.95	0.11	0.82
Background	Local zodi [Jy/sr]	1.37E+05	1.37E+05	1.37E+05	1.37E+05	1.37E+05
	Instr. brightness [Jy/sr]	2.18E-03	2.18E-03	2.18E-03	2.18E-03	2.18E-03
	Bckg fluctuations [Jy/sr]	2.17E-03	2.17E-03	2.17E-03	2.17E-03	2.17E-03
	Output flux [Jy]	4.91E-06	4.91E-06	4.91E-06	4.91E-06	4.91E-06
	Output flux [ph-el/s]	9.32E-03	9.32E-03	9.32E-03	9.32E-03	9.32E-03
Noises	Shot noise [ph-el/s^0.5]	13.21	14.04	3.85	1.55	8.83
	Detector noise [ph-el/s^0.5]	1.00	1.00	1.00	1.00	1.00
	Instrumental nulling noise [ph-el/s]	0.241	0.273	0.020	0.018	0.349
	Leakage calibration noise [ph-el/s]	0.165	0.188	0.014	0.002	0.077
	Bckg fluctuation noise [ph-el/s]	4.91E-09	4.91E-09	4.91E-09	4.91E-09	4.91E-09
SNR	Integration time [sec]	3.60E+03	3.60E+03	3.60E+03	3.60E+03	3.60E+03
	Photometric SNR	45.18	37.61	14.40	3.57	5.52
	Instrumental SNR	41.39	32.33	46.82	6.22	2.34
	Calibration SNR	60.62	46.87	68.91	47.95	10.60
	Bckg fluctuation SNR	2.03E+09	1.80E+09	1.95E+08	2.24E+07	1.67E+08
	Total SNR	27.26	21.73	13.50	3.09	2.11

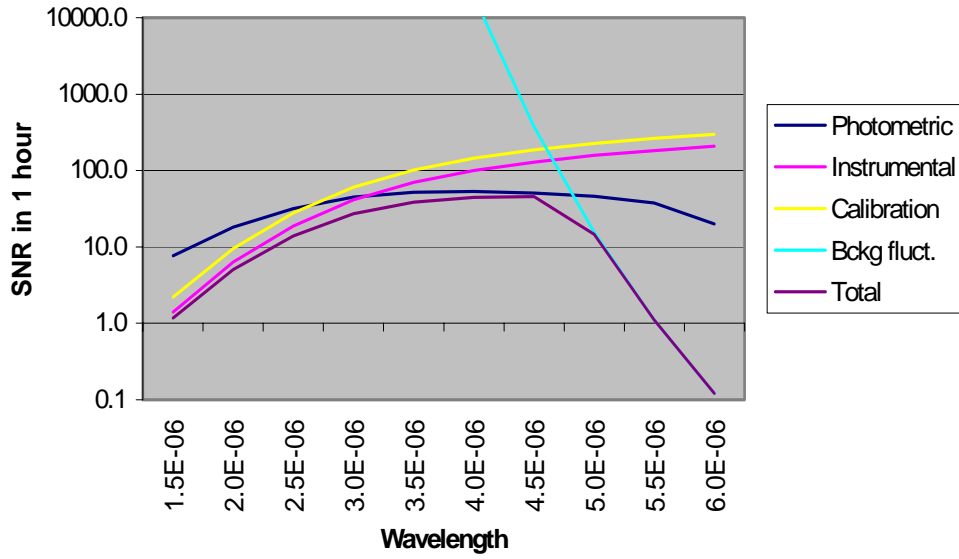**Table 1:** Expected performance for hot exoplanet detection with PEGASE.

Figure 2: Expected SNR for Tau Bootis b in one hour as a function of wavelength for a spectral resolution of 60 and a baseline of 90 m. The photometric SNR increases as integration time increases, while the three other contributors remain constant. The instrumental noise is limiting the total SNR at short wavelengths because OPD and pointing errors are more severe at those wavelengths. Background noise sets a limit on the SNR at long wavelengths as the thermal emission steeply increases with wavelength for a ~100 K blackbody.

IV. Discussion and conclusion

The simulated performance of the NIR nulling instrument onboard PEGASE is quite encouraging: the final **SNR** for our selected hot Jupiters ranges **from 3 to 27 in one hour of integration**, while the hypothetical hot Uranus is almost within reach. Fig. 1 shows that the SNR **strongly decreases at long wavelengths** due to background emission. The wavelength range could thus be slightly reduced in order to make the instrument (incl. detector) easier to manufacture. Of particular importance is the **control of the configuration**, viz. OPD and pointing control. According to preliminary studies, the tight specifications (3 nm OPD jitter, 50 mas pointing jitter) should be achievable thanks to the bright targets of PEGASE. *About 12 hot Jupiter targets can be observed with an SNR of 3 or more and a spectral resolution of 60 within one hour of integration*. This will allow to constrain their physical nature: radius/mass ratio, chemical composition, thermalization of the atmosphere, ...